

Human Exploration of Mars Design Reference Architecture 5.0

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This paper provides a summary of the 2007 Mars Design Reference Architecture 5.0 (DRA 5.0) [1], which is the latest in a series of NASA Mars reference missions. It provides a vision of one potential approach to human Mars exploration including how Constellation systems can be used. The reference architecture provides a common framework for future planning of systems concepts, technology development, and operational testing as well as Mars robotic missions, research that is conducted on the International Space Station, and future lunar exploration missions. This summary the Mars DRA 5.0 provides an overview of the overall mission approach, surface strategy and exploration goals, as well as the key systems and challenges for the first three human missions to Mars.

TABLE OF CONTENTS

1. HISTORICAL BACKGROUND	1
2. GOALS AND OBJECTIVES	1
3. DRA 5.0 OVERVIEW	7
4. VEHICLE AND SYSTEMS OVERVIEW	11
5. KEY CHALLENGES	21
6. SUMMARY	23
ACKNOWLEDGEMENTS	24
REFERENCES.....	24
BIOGRAPHIES.....	25

1. HISTORICAL BACKGROUND

During the past several years NASA has either conducted or sponsored numerous studies of human exploration beyond low-Earth Orbit (LEO) [2, 3, 4, 5, 6, 7, 8, 9]. These studies have been used to understand requirements for human exploration of the Moon and Mars in the context of other space missions and research and development programs. Each of these exploration architectures provides an end-to-end mission reference against which other mission and technology concepts can be compared. The results from the architecture studies are used by NASA to

- Derive technology research and development plans
- Define and prioritize requirements for precursor robotic missions
- Define and prioritize flight experiments and human exploration mission elements, such as those involving the International Space Station (ISS), lunar surface systems, and space transportation
- Open a discussion with international partners in a manner that allows identification of potential interests of the participants in specialized aspects of the missions
- Provide educational materials at all levels that can be used to explain various aspects of human interplanetary exploration
- Describe to the public, media, other Federal Government organizations the feasible, long-term visions for space exploration

Each of these previous architecture studies emphasized one or many aspects that are critical for human exploration to determine basic feasibility and technology needs. Example architectural areas of emphasis include the destination, system reusability, goals and objectives, surface mobility, launch vehicles, transportation, LEO assembly, transit modes, surface power, and crew size to name a few. DRA 5.0 examined several of these aspects in an integrated manner. The strategy and results from this study have been reviewed and endorsed by the four NASA headquarters mission directorates. A complete copy of this study including more details on the results can be found at: http://www.nasa.gov/exploration/library/esmd_documents.html

2. GOALS AND OBJECTIVES

The goals for the initial human exploration of Mars can best be organized under the following taxonomy:

- Goals I-III: The traditional planetary science goals from the Mars Exploration Program Analysis Group

(MEPAG) [10] for understanding Mars Life (Goal I), Climate (Goal II), and Geology/Geophysics (Goal III).

- Goal IV: Preparation for the first human explorers, as defined by MEPAG (revision in work).
- Goal IV+: Preparation for sustained human presence.
- Goal V (Ancillary Science): This includes all scientific objectives that are unrelated to Mars, including those that are related to astrophysics, observations of the Sun, Earth, Moon, and the interplanetary environment. Note that these objectives may be important during the transit phase for missions to and from Mars.

Goal I. Determine Whether Life Ever Arose on Mars

The results of the robotic missions between now and 2025 will answer some of the questions about Mars on our current horizon, which would therefore be removed and would be replaced by new questions; this is the scientific process. Although our ability to predict the results of these future missions and the kinds of new questions that will come up is partial, we do know the kinds of data that will be collected and the kinds of questions that these data are capable of answering. Thus, we can make some general projections of the state of knowledge as of 2025.

By 2025, our assessments of habitability potential will be well advanced for some environments, particularly those that have been visited by the Mars Sample Return (MSR) or by major in-situ rovers with life-related experiments. However, it is likely that the habitability of the martian subsurface will be almost completely unexplored other than by geophysical methods. The objective relating to carbon cycling is likely to be partially complete, but in particular as related to subsurface environments. For the purpose of this planning, we assume that the investigations through 2025 have made one or more discoveries that are hypothesized as being related to ancient life (by analogy with the Allen Hills meteorite story, this is a particularly likely outcome of MSR). We should then be prepared for the following new objectives:

- Characterize the full suite of biosignatures for ancient life to confirm the past presence of life. Interpret its life processes and the origin of such life.
- Assess protected environmental niches that may serve as refugia for extant life forms that may have survived to the present. Find the life, measure its life processes.
- In earliest martian rocks, characterize the pre-biotic chemistry.

Goal II: Understanding the Processes and History of Climate on Mars

By 2025, our objectives related to characterization of the Mars atmosphere and its present and ancient climate

processes are likely to be partially complete. In addition to continuing long-term observations, our scientific questions seem likely to evolve in the following directions. Note in particular that if there is no robotic mission to one of the polar caps, the priority of that science is likely to be significantly more important than it is today because of the influence of polar ice on the climate system.

- Quantitative understanding of global atmospheric dynamics.
- Understand microclimates – range of variation, how and why they exist.
- Perform weather prediction.
- Understand the large-scale evolution of the polar caps including the modern energy balance, links with dust, carbon dioxide (CO₂), and H₂O cycles, changes in deposition and erosion patterns, flow, melting, age, and links between the two caps.

Goal III: Determine the Evolution of the Surface and Interior of Mars

As of 2006, there were two primary objectives within this goal: (1) Determine the nature and evolution of the geologic processes that have created and modified the martian crust and surface, and (2) characterize the structure, composition, dynamics, and evolution of the martian interior. These are broadly enough phrased that they are likely to still be valid in 2025. These two objectives, for example, currently apply to the study of the Earth, even after more than 200 years of geologic study by thousands of geologists. Given the anticipated robotic missions leading up to the first human missions, the first objective is likely to evolve in the following direction:

- Quantitatively characterize the different components of the martian geologic system (at different parts of martian geologic history), and understand how these components relate to each other.
- Understand the field context of the various martian features of geologic interest at both regional and local scale.
- Test specific hypotheses.
- Perform comparative planetology.

Goal IV: Preparing for Human Exploration of Mars

Goal IV addresses the precursor measurements of Mars needed to reduce the risk of the first human mission to Mars. MEPAG is currently updating Goal IV objectives as derived from Mars DRA 5.0. Since this process is still underway, the results of this reformulation cannot be discussed here.

Goal IV+: Preparing for Sustained Human Presence

Goal IV+ specifically focuses on Mars human habitability, exploration systems development, and long-duration space mission operations necessary for sustained human presence. Goal IV+ focuses on the objectives for the first three human Mars missions that would support the performance of human Mars missions four through ten. The scope of the representative scenarios for missions four through ten includes developing the knowledge, capabilities, and infrastructure that are required to live and work on Mars, with a focus on developing sustainable human presence on Mars.

Goal V: Ancillary Science

Potential science objectives that are appropriate to the initial human missions to Mars extend beyond those relating solely to the scientific exploration of Mars as a planet or the preparation for a sustained human presence on Mars. As a unique planetary specimen, Mars is relevant to the study of the entire solar system, including its evolution under the influence of the sun (Heliophysics), and to the study of the solar system as an important specimen of stellar evolution (Astrophysics), as well as other science disciplines. In addition, Mars may be a unique location from which to perform certain astrophysical observations.

Taking advantage of the unique attributes of humans in scientific exploration

It is important to consider the unique capabilities that humans bring to the process of exploring Mars. As a result, a common set of human traits emerged that apply to exploration relating to the MEPAG science disciplines, which include geology, geophysics, life, and climate. These characteristics include: speed and efficiency to optimize field work; agility and dexterity to go places that are difficult for robotic access and to exceed currently limited degrees-of-freedom robotic manipulation capabilities; and, most importantly, the innate intelligence, ingenuity, and adaptability to evaluate in real time and improvise to overcome surprises while ensuring that the correct sampling strategy is in place to acquire the appropriate sample set. Real-time evaluation and adaptability especially would be a significant new tool that humans on Mars would bring to surface exploration. There are limitations to the autonomous operations that are possible with current robotic systems, with fundamental limitations to direct commanding from Earth being the time difference imposed by the 6- to 20-minute communications transit time and the small number of daily uplink and downlink communications passes. The scientific exploration of Mars by humans would presumably be performed as a synergistic partnership between humans and robotic probes – a partnership that is controlled by the human explorers on the surface of Mars [11].

Initial Human Exploration of Mars Objectives Related to Goals I-III

Geology Scientific Objectives— Some of the most important questions about Goals I through III involve the relationship of H₂O to martian geologic and biologic processes as a function of geologic time. Mars has apparently evolved from a potentially “warm and wet” period in its early Noachian history to the later “cold and dry” period of the Amazonian period. Since rocks of different age are exposed in different places on Mars, understanding this geologic history requires an exploration program that also involves spatial diversity. One of the realities of geology-related exploration is that samples and outcrops are typically representative only of a certain geologic environment, and that acquiring information about other environments requires going to a different place. (A terrestrial analog would be asking how much we could learn about Precambrian granite by doing field work in the sedimentary rocks of the Great Plains.)

The absolute ages of surface units on Mars have been deciphered through indirect methods. Samples returned from the moon in the Apollo Program were used to provide constraints on the crater-size frequency distribution of the lunar surface [12, 13], and this has been applied to Mars, among other terrestrial planetary bodies [14, 15, 16]. While this has provided a general history of martian surface processes, it does not allow for detailed study of specific martian periods, in particular the Hesperian and Amazonian periods when the impact flux greatly decreased. While martian meteorites have been analyzed and dated [17], not knowing their geologic context makes their incorporation into the geologic history of Mars difficult. While an MSR mission could potentially yield surface samples with known context, a robotic mission would not yield the array of optimal samples that would address a wide range of fundamental questions. A human mission might allow for greater access to samples that a robotic rover might not get to, and the capacity for real-time analysis and decision-making would ensure that the samples obtained that were would be the optimal available samples.

Human explorers would also have greater access to the near-subsurface of Mars, which would yield insights into climate and surface evolution, geophysics, and, potentially, life. Humans would be able to navigate more effectively through blocky ejecta deposits, which would provide samples that were excavated from great depth and provide a window into the deeper subsurface. Humans could trench in dozens of targeted locations and operate sophisticated drilling equipment that could drill to a depth of 500 to 1,000 meters below the surface. Our current understanding of the crust of Mars is limited to the top meter of the surface, so drilling experiments would yield unprecedented and immediate data. Drilling in areas of gully formation could also test the groundwater model by searching for a confined aquifer at depth.

We have analyzed three different exploration sites in detail as reference missions for the first program of human Mars exploration. The sites, which span the geologic history of Mars (one site for each period of martian history), allow for exploration traverses that would examine a variety of surface morphologies, textures, and mineralogy to address the fundamental questions posed by the MEPAG.

Geophysics Scientific Objectives— Mars geophysics science objectives fall into two broad categories: planetary scale geophysics (thousands of kilometers), and what might be called “exploration geophysics,” which addresses regional (tens to hundreds of kilometers) or local scales (<10 km). The first category involves characterizing the structure, composition, dynamics, and evolution of the martian interior, while the second category addresses the structure, composition, and state of the crust, cryosphere, hydrologic systems, and upper mantle. Here we describe how these objectives might be met through investigations carried out on human missions. We assume here that no robotic missions to Mars before 2025 address the science issues in a complete way. For example, we assume that no network missions (National Research Council [18]) will be flown. In general, Mars geophysics will be well served by the diversity of landing sites needed to pursue the geological and life-related objectives.

To characterize the structure and dynamics of Mars’ interior band, we must determine the chemical and thermal evolution of the planet, including physical quantities such as density and temperature with depth, composition and phase changes within the mantle, the core/mantle boundary location, thermal conductivity profile and the 3-dimensional mass distribution of the planet. To determine the origin and history of the planet’s magnetic field, we must discover the mineralogy responsible for today’s observed remnant magnetization, and understand how and when the rocks bearing these minerals were emplaced. A key driver is the need to instrument the planet at appropriate scales: e.g., global seismic studies rely on widely separated stations so that seismic ray paths passing through the deep mantle and core can be observed. This need translates into multiple, widely separated landing sites for the first human missions. If only a single landing site is selected and revisited, far less information about Mars’ interior will be obtained. A wide variety of exploration geophysics techniques could be brought to bear, including sounding for aquifers through electromagnetic techniques and reflection seismology to determine local structure. Magnetic surveys that are carried out at landing sites tell us about the spatial scales of crustal magnetization, and tie in to local and regional geology for context.

Geophysics measurement requirements span three disparate spatial scales, depending on the science that is to be done. At the largest scales (thousands of kilometers), characterizing the interior of Mars requires a widely spaced network of at least three emplaced central geophysics

stations, one at each landing site. At regional scales (tens to thousands of kilometers), characterizing crustal structure, magnetism, and other objectives requires mobility to emplace local networks around a landing site. Finally, at local scales (10 km), mobility is key to performing traverse geophysics, and in carrying out investigations (such as seismic or electromagnetic sounding) at specific stations along a traverse. The central geophysics stations and the regional scale networks would be emplaced and left to operate autonomously after the human crew departs. Traverse and station geophysics would be carried out only during the human mission, unless this could be done robotically after completion of the human mission.

Central geophysical stations at each landing site would include passive broadband seismic, heat flow, precision geodesy, and passive low-frequency electromagnetic instrumentation. Satellite geophysics stations would include the nodes of a regional seismic array and vector magnetometers. Along the traverses, experiments would be performed at sites of interest. These would include active electromagnetic (EM) sounding for subsurface aquifers, active seismic profiling to establish structure with depth, and gravity measurements. Ground-penetrating radar and neutron spectroscopy along the traverse track help map out subsurface structure and hydration state/ice content for the near-subsurface.

Atmosphere/Climate Scientific Objectives— In the human era of exploration, atmospheric measurements at all sites would be seen as important not only to understanding Mars’ atmosphere and climate and to planning human surface operations, but also as an environmental characterization that is essential to the interpretation of many life and geology objectives. The trend towards system science called out in MEPAG [10] as a “ground-to-exosphere approach to monitoring the martian atmospheric structure and dynamics” will continue with more emphasis on the mass, heat, and momentum fluxes between the three Mars climate components: atmosphere, cryosphere, and planetary surface.

Understanding Mars’ past climate will benefit from anticipated new knowledge of current atmospheric escape rates that will be gained from the 2013 Mars Aeronomy Scout. However, a significant advancement in the key area of access to the polar stratigraphic record is not expected in the decades before human exploration. In 2030, this will therefore remain one of the highest priorities for MEPAG. On the other hand, the study of the paleoclimatic parameters that are imprinted in the ancient geological record (e.g., Noachian to Amazonian periods) also concerns the high priorities of the MEPAG, which directly relates to unlocking the ancient climatic conditions of Mars through a physical (e.g., geomorphic and/or sedimentary), petrological, mineral, and geochemical (including isotopic) material characterization.

The emphasis of atmospheric science measurements by human missions would likely focus on processes within the planetary boundary layer (PBL), which is surface to 2 km, where surface-atmosphere interactions impart fundamental influences on the dynamical, chemical, and aerosol characters of the global Mars atmosphere. For the PBL, all spatial scales are important in turbulent exchange, from centimeters to kilometers, in both horizontal and vertical dimensions. Human atmospheric observations could provide optimum in-situ and remote access to the PBL and, in turn, characterize local environmental conditions in support of human operations.

- **Atmospheric dynamics.** This is important because it determines the basic thermal structure of the martian atmosphere, the global transport of volatiles (CO_2 , H_2O , dust), and the maintenance of the martian polar ice caps, all of which vary on seasonal and inter-annual timescales.
- **Atmospheric Dust.** Atmospheric heating that is associated with atmospheric dust intensifies global atmospheric circulation and near-surface winds, which in turn increases lifting of surface dust into the atmosphere.
- **Atmospheric Water:** Atmospheric H_2O , in the form of vapor and ice clouds, plays significant roles in atmospheric chemistry, dust radiative forcing, and climate balance.
- **Atmospheric Chemistry:** The trace chemical composition of the current martian atmosphere reflects the photochemical cycles that are associated with the major atmospheric constituents CO_2 , H_2O , and nitrogen (N_2); and perhaps non-equilibrium chemistry that is associated with potential subsurface sources – sinks of methane (CH_4), sulfur dioxide (SO_2) and hydrogen peroxide (H_2O_2) [19; 20].
- **Electrical Effects:** Experimental and theoretical investigations of frictional charging mechanisms in both small and large-scale meteorological phenomena suggest that Mars very likely possesses an electrically active atmosphere as a result of dust-lifting processes of all scales, including dust devils and dust storms. Electrical effects impact human exploration and the environment of Mars as a source of both continual and episodic energy.

Biology/Life Scientific Objectives—Human-enabled biological investigations on Mars would focus on taking samples and making measurements to determine whether life ever arose on Mars. This goal is consistent with the 2006 MEPAG goals and priorities, and we do not see this goal changing within the next 30 years.

The search for life on Mars can be generally broken into two broad categories: (1) the search for evidence of past life on Mars, which may or may not still be alive; and (2) the search for present (extant) life. Both have been, and will

continue to be, based on a search for H_2O , since all life on Earth requires H_2O for survival. Abundant evidence on the martian surface of past H_2O activity (e.g., rivers, lakes, groundwater discharge) has led to Mars becoming a strong candidate as a second planet in our solar system with a history of life. With our increasing knowledge of the extremes under which organisms can survive on Earth, especially in the deep subsurface, whether martian life is still present today has become a compelling and legitimate scientific question.

As pointed out by the NRC [21], the search for life on Mars requires a very broad understanding of Mars as an integrated planetary system. Such an integrated understanding requires investigation of the following:

- The geological and geophysical evolution of Mars;
- The history of Mars' volatiles and climate;
- The nature of the surface and the subsurface martian environments;
- The temporal and geographical distribution of H_2O ;
- The availability of other resources (e.g., energy) that are necessary to support life; and
- An understanding of the processes that control each of the factors listed above.

The search for extant life—The NRC [21] suggests a number of high-priority targets based on evidence for present-day or geologically recent H_2O near the surface. These targets are

- The surface, interior, and margins of the polar caps;
- Cold, warm, or hot springs or underground hydrothermal systems; and
- Source or outflow regions that are associated with near-surface aquifers that might be responsible for the “gullies” that have been observed on the martian surface.

The MEPAG Special Regions Science Analysis Group [10] noted that the sites where recent H_2O may have occurred might also include some mid-latitude deposits that are indicative of shallow ground ice. Conditions in the top 5 m of the martian surface are considered extremely limiting for life. Limiting conditions include high levels of ultraviolet radiation and purported oxidants as well as most of the surface being below the limits of H_2O activity and temperature for life on Earth. For these reasons, finding evidence of extant life near the martian surface will likely be difficult, and the search will almost certainly require subsurface access. This was also a key recommendation of the National Research Council [21].

The search for past life—The NRC [21] lists sites that are pertinent to geologically ancient H₂O (and, by association, the possibility of past life), including the following:

- Source or outflow regions for the catastrophic flood channels;
- Ancient highlands that formed at a time when surface H₂O might have been widespread (e.g., in the Noachian); and
- Deposits of minerals associated with surface or subsurface H₂O or with ancient hydrothermal systems or cold, warm, or hot springs.

Objectives Related to Preparation for Sustained Human Presence (Goal IV+)

MEPAG's Goal IV is interpreted to be related to preparation for the first human explorers, so by definition, it will be complete before the initial set of human missions has been attempted or the activity will have been shown not to be necessary. We refer to Goal IV+ as the preparation for the sustained human presence on Mars beyond that of the DRA 5.0 mission set. Specific objectives within Goal IV+ could be carried out either within the context of the DRA 5.0 missions, or by the preceding robotic program. The scope of the representative scenarios includes developing the knowledge, capabilities, and infrastructure that are required to live and work on Mars, with a focus on developing sustainable human presence on Mars.

- **Habitability:** Includes the capability (1) of providing crew needs from local resources, (2) of extracting power and propulsion consumables from local resources, and (3) for in-situ fabrication and repair.
- **Systems Development:** Includes objectives which relate to the establishment of reliable and robust space systems that would enable gradual and safe growth of capabilities.
- **Self-sufficiency:** The level of self-sufficiency of operations for Mars missions also must increase and, hence, is the objective in the Operational Capabilities area.
- **Other Objectives:** Which address planetary protection concerns, partnerships, and public engagement, insofar as these are concerned.

Objectives Related to Ancillary Science (Goal V)

Heliophysics of Mars' environment—The martian system, as an archive of solar system evolution (space climate) and a case of planetary interfaces responding to immediate solar influences (space weather), is of great interest to the science of Heliophysics. These influences range from solar irradiance and high-energy particles irradiating the planet's surface, to solar wind and magnetic fields driving

disturbances of the martian atmosphere and ionosphere. Mars also represents an important key instance of fundamental Heliophysical processes that influence the habitability of planets. Because the space environment matters to the safety and productivity of humans and their technological systems both at Mars and in transit, it is essential that we monitor Heliophysical conditions between Earth and Mars and understand solar effects on the martian atmosphere, which are relevant for vehicles in Mars orbit or traveling through the atmosphere to the surface environment. An important supporting objective is to understand the influence of planetary plasmas and magnetic fields and their interaction with the solar wind plasma.

Space weather— The sun and interplanetary medium permeating our solar system, as well as the universe at large, consist primarily of plasmas. This leads to a rich set of interacting physical processes and regimes, including intricate exchanges with the neutral gas environments of planets. In preparation for travel through this environment, human explorers must anticipate and prepare for encounters with hazardous conditions stemming from ionizing radiation. Among the many questions to be answered, the following are perhaps the most significant: What are the mean conditions, variability, and extremes of the radiation and space environment for exploration of Mars? How does the radiation environment vary in space and time, and how should it be monitored and predicted for situational awareness during exploration? What is the relative contribution from solar energetic particles and cosmic radiation behind the various shielding materials that are used and encountered, and how does this vary?

Laser ranging for astrophysics— While observations from free space offer the most promise for significant progress in broad areas of astrophysics, some investigations could be uniquely enabled by the infrastructure and capabilities of a human mission to Mars. Among the most promising in this respect are laser ranging experiments to test a certain class of alternative theories (to general relativity) of gravity. Such experiments become even more valuable when considered in the context of a humans-to-Mars architecture. The long baseline measurements that are afforded by laser ranging from Mars provides a unique capability that would otherwise not be enabled by free space implementations or via a lunar architecture.

Goals and Objectives Summary Implications

During the development of the Mars Design Reference Architecture 5.0, options were developed to provide a better understanding of the relationship between the various exploration goals and objectives and resulting implementation approaches of meeting those goals. Deliberations resulted in the following summary implications:

Explore the Same Site or Different Sites? — Over the last decade, exploration of Mars by robotic orbiters, landers, and rovers has shown Mars to be a planet of great diversity and complexity. This diversity and complexity offers a unique opportunity for humans on the surface of Mars to obtain data and measurements that could not be obtained by robotic probes alone. To use human explorers effectively in addressing these scientific questions, the first three human missions to Mars should be to three different geographic sites. The Goal IV+ objectives lend themselves best to repeated visits to a specific site on Mars, however. Repeated site visits would enable a buildup of infrastructure that would benefit the longer-term missions of the Goal IV+ objectives. This buildup would provide more systems for use by the crews such as habitable volume, mobility aids, and science equipment. These systems and the potential for spares could also potentially reduce the amount of logistics required for the long-term missions.

Short Stay or Long Stay? — It is clear that productivity of the missions is amplified many-fold in a 500-day scenario as compared to a 30-day scenario. This is particularly true of scientific objectives that are related to geology and the search for life, for which we need to maximize the amount of time that the astronauts spend examining the rocks and the diversity of the samples that are collected. Longer stays allow for a more comprehensive characterization of certain environmental parameters and a longer baseline of measurements. This specific and long-duration knowledge will be essential in the development of health monitoring and hazard mitigation strategies for both the crew and infrastructure elements. The systems required for long stays are also more supportive of the eventual longer term missions that would achieve sustained human presence

Degree of Mobility— Achieving these scientific objectives would require mobility. Although different possible landing sites have different spatial relationships, it is possible to estimate that the capability of traveling a radial distance of several hundred kilometers would allow a full range of landing site options.

Subsurface access— It is possible that drilling depths in the range of 100 to 1000 m would be necessary, depending on the drilling site and the goal of the drilling.

Returned sample science— Since human missions to Mars have a round-trip component to them, they naturally lend themselves to returned sample science. To maximize the value of the returned sample collection, it would be necessary to have a habitat laboratory for two purposes: (1) to help guide them on-Mars field strategies and (2) to ensure the high grade of the samples to be returned. Sample conditioning and preservation will be essential. The minimum mass of samples to be returned to Earth is to be determined, but it could be as much as 250 kg.

Instruments that operate after humans leave— Several types of monitoring stations should be configured so that they can continue operating after the astronauts leave. This would specifically include network stations for seismic monitoring and long-duration climate monitoring.

Planetary protection— The impact of human explorers and potential “human contamination” of the martian environment in the search for present-day life on Mars is a problem that requires more study and evaluation, and that must be solved prior to the first human landing on Mars.

Given that the engineering of missions to Mars are constrained to be either “short stay” or “long stay” and assuming that the initial human exploration of Mars consists of a program of three missions, a key tradeoff is mission duration and whether the missions are sent to the same or to different sites. **From the perspective of our scientific goals, it is clear that our progress would be optimized by visiting multiple sites and by maximizing the stay time at those sites.** The same argument regarding diversity of sites was raised, and followed, during the Apollo Program. The longer stay time is needed because the geology of Mars at many sites has complexities that would take a significant amount of time to resolve. If we are to bring the unique attributes of human explorers to bear, we would need to give them enough time on the outcrops.

3. DRA 5.0 OVERVIEW

The NASA Design Reference Architecture 5.0 envisions sending six crewmembers to Mars on a minimum of three consecutive opportunities. The rationale for a crew of this size has been judged to be a reasonable compromise between the skill mix and level of effort for missions of this complexity and duration balanced with the magnitude of the systems and infrastructure needed to support the crew. One of the primary objectives for future human exploration of Mars is to understand the global context of the history of Mars, and thus each mission would visit a different unique location on Mars. The science and exploration rationale for visiting three different sites recognizes that a planet that is as diverse as Mars is not likely to be adequately explored and understood from the activities that could take place at a single site. However, this three-site assumption does not preclude returning to any of the sites should there be a compelling need to do so. This approach was endorsed by the Human Exploration of Mars Science Advisory Group, which is an independent science team sponsored by MEPAG [22].

Each of the three missions would use conjunction class (long-stay) trajectories combined with a “forward deploy” cargo strategy. A portion of each mission’s assets would be sent to Mars one opportunity prior to the crew. This forward deploy strategy would allow lower energy trajectories to be used for these pre-deployed assets, which allows more

useful payload mass to be delivered to Mars for the propellant available. The decision to pre-position some of the mission assets also better accommodates the strategy to make part of the ascent propellant at Mars, using the martian atmosphere as the raw material source for this ascent propellant. This use of in-situ resources and the equipment to process these resources into useful commodities results in a net decrease in the total mass that is needed to complete a mission as well as a significant reduction in the size of the landers. A surface nuclear power source would be utilized for producing this ascent propellant as well as for providing power for the surface systems once the crew arrives. Splitting the mission elements between pre-deployed cargo and crew vehicles allows the crew to fly on faster, higher-energy trajectories, thus minimizing their exposure to the hazards associated with deep-space inter-planetary travel.

Getting Ready, Getting to Mars, and Getting Back

Due to the significant amount of mass required for a human mission to Mars, numerous heavy-lift launches would be required. The reference launch vehicle that would be used is the Ares V launch vehicle. Using the same launch vehicle currently envisioned for lunar missions would greatly improve the overall mission risk due to the improved maturity of the launch vehicle by the time the Mars missions commence. Current estimates of the mission manifest indicate that at least seven heavy-lift cargo launches would be required, but the number of launches could be higher, depending on the architecture-wide technology options inserted. This large number of launches necessitates a launch campaign that must begin several months prior to the opening of the Mars departure window. The reference strategy that is adopted eliminates on-orbit assembly of the mission elements by segmenting the systems into discrete packages and using automated rendezvous and docking (AR&D) of the major elements in LEO. Launches would occur 30 days apart and would be completed several months before the opening of the Mars departure window to provide a margin for technical delays and other unforeseen problems. This strategy requires that the in space transportation systems and payloads loiter in LEO for several months prior to departure for Mars. The overall launch and flight sequence for the first two missions is depicted in figure 1.

The first phase of the mission architecture would begin with the pre-deployment of the first two cargo elements, the descent/ascent vehicle (DAV) and the surface habitat (SHAB). These two vehicle sets would be first launched, assembled (via rendezvous and docking), and checked out in LEO. After all of the systems have been verified and are operational, the vehicles loiter in Earth orbit until the Earth-Mars departure window opens when they would be injected into minimum energy transfers from Earth orbit to Mars just over 2 years prior to the launch of the crew. Upon arrival at Mars, the vehicles would be captured into a highly elliptical

Mars orbit. The SHAB would remain in Mars orbit in a semi-dormant mode, waiting for arrival of the crew 2 years later. The DAV would be captured into a temporary Mars orbit from which it would autonomously perform the entry, descent, and landing on the surface of Mars at the desired landing site. After landing, the vehicle would be checked out and its systems verified to be operational. The surface fission reactor would be deployed, and production of the ascent propellant and other commodities that are needed by the crew would be completed before committing to the crew phase of the mission.

A key feature of the long-stay mission architecture is the autonomous deployment of a portion of the surface infrastructure before the crew arrives, such as the surface power system. This strategy includes the capability for these infrastructure elements to be unloaded, moved significant distances, and operated for significant periods of time without humans present. In fact, the successful completion of these various activities would be part of the decision criteria for launch of the first crew from Earth.

The second phase of this architecture begins during the next injection opportunity with the launch, assembly, and checkout of the crew Mars transfer vehicle (MTV). The MTV would serve as the interplanetary support vehicle for the crew for a round-trip mission to Mars orbit and back to Earth. Prior to departure of the flight crew, a separate checkout crew may be delivered to the MTV to perform vital systems verification and any necessary repairs prior to departure of the flight crew. After all vehicles and systems, including the Mars DAV (on the surface of Mars), SHAB (in Mars orbit), and the MTV (in LEO) are verified operational, the flight crew would be injected on the appropriate fast-transit trajectory towards Mars. The length of this outbound transfer to Mars is dependent on the mission date, and ranges from 175 to 225 days. Upon arrival at Mars, the crew members perform a rendezvous with the SHAB, which would serve as their transportation leg to the surface of Mars.

Current human health and support data indicate that it may take the crew a few weeks to acclimate to the partial gravity of Mars after landing. After the crew has acclimated, the initial surface activities would focus on transitioning from a “lander mode” to a fully functional surface habitat. This would include performing all remaining setup and checkout that could not be performed prior to landing, as well as transfer of hardware and critical items from the pre-deployed DAV.

The long-stay mission architecture lends itself to a very robust surface exploration strategy. The crew would have approximately 18 months in which to perform the necessary surface exploration. Ample time would be provided to plan and re-plan the surface activities, respond to problems, and readdress the scientific questions posed throughout the

useful payload mass to be delivered to Mars for the propellant available. The decision to pre-position some of the mission assets also better accommodates the strategy to make part of the ascent propellant at Mars, using the martian atmosphere as the raw material source for this ascent propellant. This use of in-situ resources and the equipment to process these resources into useful commodities results in a net decrease in the total mass that is needed to complete a mission as well as a significant reduction in the size of the landers. A surface nuclear power source would be utilized for producing this ascent propellant as well as for providing power for the surface systems once the crew arrives. Splitting the mission elements between pre-deployed cargo and crew vehicles allows the crew to fly on faster, higher-energy trajectories, thus minimizing their exposure to the hazards associated with deep-space inter-planetary travel.

Getting Ready, Getting to Mars, and Getting Back

Due to the significant amount of mass required for a human mission to Mars, numerous heavy-lift launches would be required. The reference launch vehicle that would be used is the Ares V launch vehicle. Using the same launch vehicle currently envisioned for lunar missions would greatly improve the overall mission risk due to the improved maturity of the launch vehicle by the time the Mars missions commence. Current estimates of the mission manifest indicate that at least seven heavy-lift cargo launches would be required, but the number of launches could be higher, depending on the architecture-wide technology options inserted. This large number of launches necessitates a launch campaign that must begin several months prior to the opening of the Mars departure window. The reference strategy that is adopted eliminates on-orbit assembly of the mission elements by segmenting the systems into discrete packages and using automated rendezvous and docking (AR&D) of the major elements in LEO. Launches would occur 30 days apart and would be completed several months before the opening of the Mars departure window to provide a margin for technical delays and other unforeseen problems. This strategy requires that the in space transportation systems and payloads loiter in LEO for several months prior to departure for Mars. The overall launch and flight sequence for the first two missions is depicted in figure 1.

The first phase of the mission architecture would begin with the pre-deployment of the first two cargo elements, the descent/ascent vehicle (DAV) and the surface habitat (SHAB). These two vehicle sets would be first launched, assembled (via rendezvous and docking), and checked out in LEO. After all of the systems have been verified and are operational, the vehicles loiter in Earth orbit until the Earth-Mars departure window opens when they would be injected into minimum energy transfers from Earth orbit to Mars just over 2 years prior to the launch of the crew. Upon arrival at Mars, the vehicles would be captured into a highly elliptical

Mars orbit. The SHAB would remain in Mars orbit in a semi-dormant mode, waiting for arrival of the crew 2 years later. The DAV would be captured into a temporary Mars orbit from which it would autonomously perform the entry, descent, and landing on the surface of Mars at the desired landing site. After landing, the vehicle would be checked out and its systems verified to be operational. The surface fission reactor would be deployed, and production of the ascent propellant and other commodities that are needed by the crew would be completed before committing to the crew phase of the mission.

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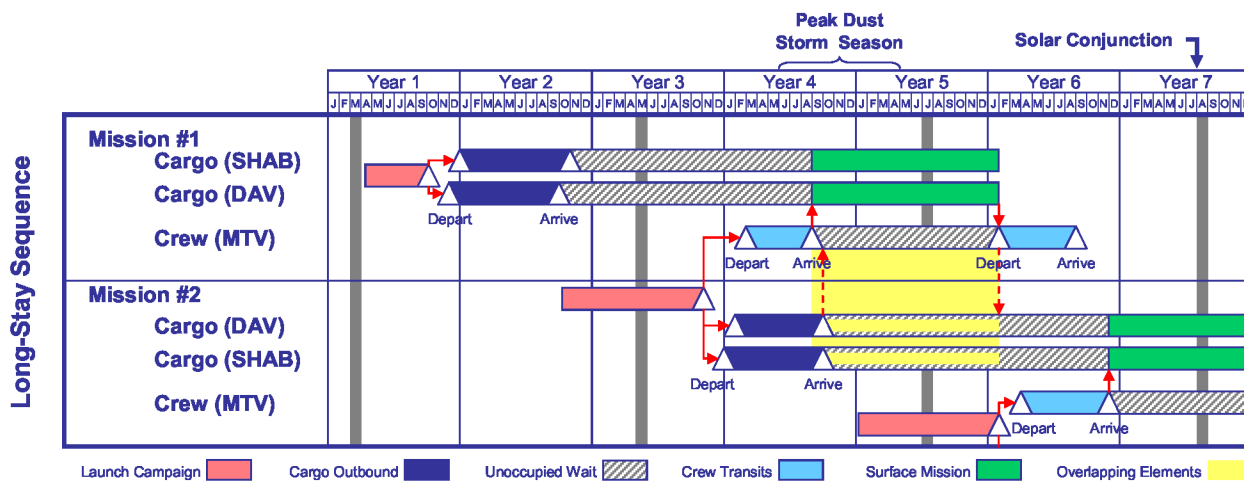


Figure 1 Mars Mission Sequence

mission. The focus during this phase of the mission would be on the primary science and exploration activities that would change over time to accommodate early discoveries. A general outline of crew activities would be established before the launch, but would be updated throughout the mission. This outline would contain detailed activities to ensure initial crew safety, make basic assumptions as to initial science activities, schedule periodic vehicle and system checkouts, and plan for a certain number of sorties.

Much of the detailed activity planning while on the surface would be based on initial findings and, therefore, could not be accomplished before landing on Mars. The crew would play a vital role in planning specific activities as derived from more general objectives defined by colleagues on Earth. Alternative approaches for exploring the surface are still under discussion and are expected to be examined further, including maximizing commonality with lunar systems. One of the approaches that most closely follows previous DRAs, referred to as the “Commuter” scenario, was selected as the nominal approach and is described in the next section.

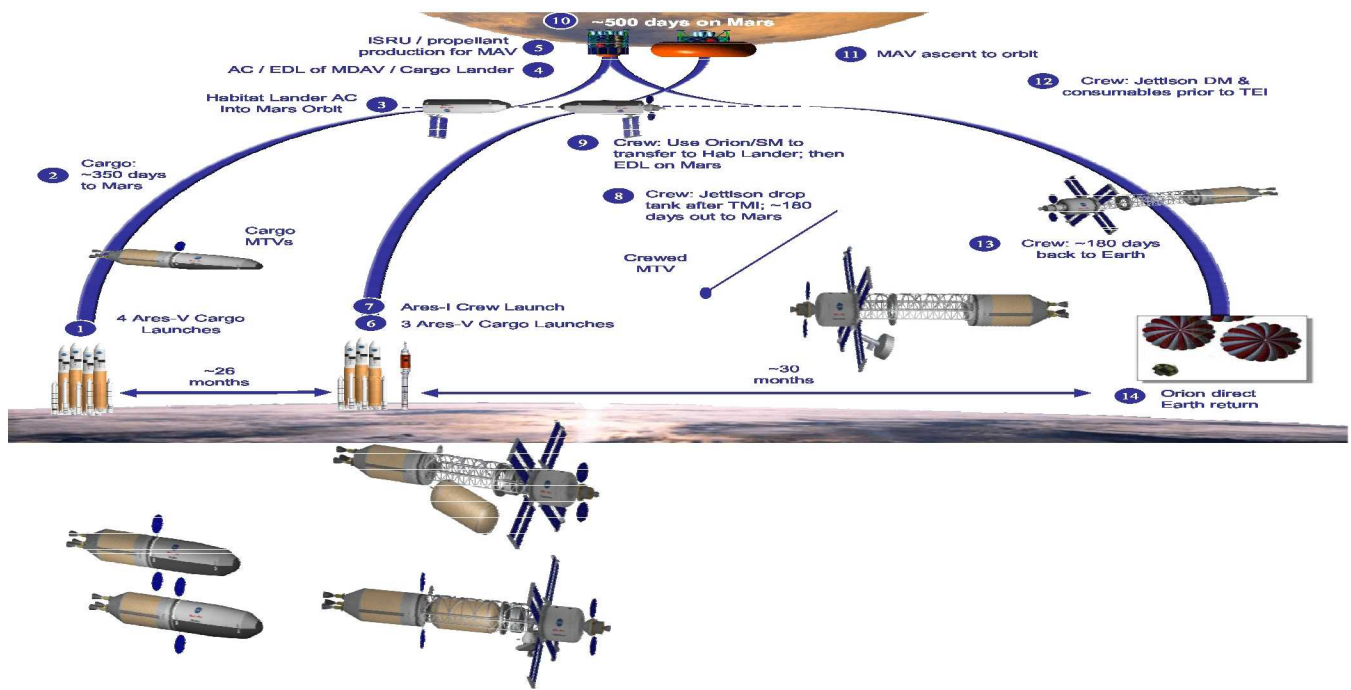
Before committing the crew to Mars ascent and return to Earth, full systems checkout of the ascent vehicle and the MTV would be required. Because both vehicles are critical to crew survival, sufficient time must be provided prior to ascent to verify systems and troubleshoot any anomalies prior to crew use. In addition, the surface systems would be placed in a dormant mode for potential reuse by future crews by stowing any nonessential hardware, safing critical systems and their backups, and performing general housekeeping duties. Lastly, some surface elements would be placed in an automated operations mode for Earth-based control so that scientific observations could be continued after the crew has departed. The crew would then ascend in the DAV and performs a rendezvous with the waiting MTV.

This vehicle would be used to return the crew from Mars, ending with a direct entry at Earth in a modified Orion crew vehicle. The nuclear thermal rocket version of the DRA, also known as a “bat chart”, is shown in figure 2.

Exploring the Surface

Candidate surface sites would be chosen based on the best possible data available at the time of the selection, the operational difficulties associated with that site, and the collective merit of the science and exploration questions that could be addressed at the site. Information available for site selection would include remotely gathered data sets plus data from any landed mission(s) in the vicinity plus interpretive analyses based on these data.

Several different surface architectures were assessed during the formulation of the Mars DRA 5.0, each of which emphasized different exploration strategies that were embodied in the combination of duration of in the field, range of exploration reach, and depth of subsurface access. The nominal surface mission scenario adopted for DRA 5.0 is the so-called “Commuter” reference architecture, which would have a centrally located, monolithic habitat, two small pressurized rovers, and two unpressurized rovers (roughly equivalent to the lunar rover vehicle (LRV) that was used in the Apollo missions to the moon). This combination of habitation and surface mobility capability would allow the mission assets to land in relatively flat and safe locations, yet provides the exploration range that would be necessary to reach nearby regions of greater scientific diversity. Power for these systems would be supplied by a nuclear power plant that was previously deployed with the DAV and used to make a portion of the ascent propellant. Traverses would be a significant feature of the exploration strategy that would be used in this scenario, but these traverses would be constrained by the capability of the



10

Figure 2 Mars Design Reference Architecture 5.0 Mission Profile

small pressurized rover. In this scenario, these rovers have been assumed to have a modest capability, notionally a crew of two with minimum of 100 km total distance before being resupplied and 1- to 2-week duration. Thus, on-board habitation capabilities would be minimal in these rovers. However, these rovers are assumed to be nimble enough to place the crew in close proximity to features of interest (i.e., close enough to view from inside the rover or within easy extravehicular activity (EVA) walking distance of the rover). Not all crew members would deploy on a traverse, so there would always be some portion of the crew in residence at the habitat. The pressurized rovers would carry (or tow) equipment that would be capable of drilling to moderate depths – from tens to hundreds of meters – at the terminal end of several traverses.

Figure 3 illustrates a notional series of traverses to features of interest at the junction of the Isidis Planatia and Syrtis Major regions. No particular preference is being given to this site; it is included here to illustrate some general

features of a human exploration mission and the resulting implications for operations at such a site.

From an operational perspective, this location has a relatively broad, relatively flat, centrally located area where cargo elements could land in relative safety. However, this would place these systems and the crew at large distances from features that are of interest to the crew and the science teams. The scale at the lower right of figure 3 indicates that these features of interest are beyond what is currently considered a reasonable walking range for the crew (determined by the distance a crew member could walk during one charge of power and breathing gases in his/her Portable Life Support System (PLSS) – roughly 20 km total). Although sites with much more closely spaced features of interest certainly exist, they are usually found at the expense of a relatively safe landing site.

One feature of interest is not illustrated here – the subsurface. Understanding the vertical structure of the site would also be of interest, indicating that a drilling capability would need to be included for each mission and site. The ability to move a drill from location to location would also be desirable.

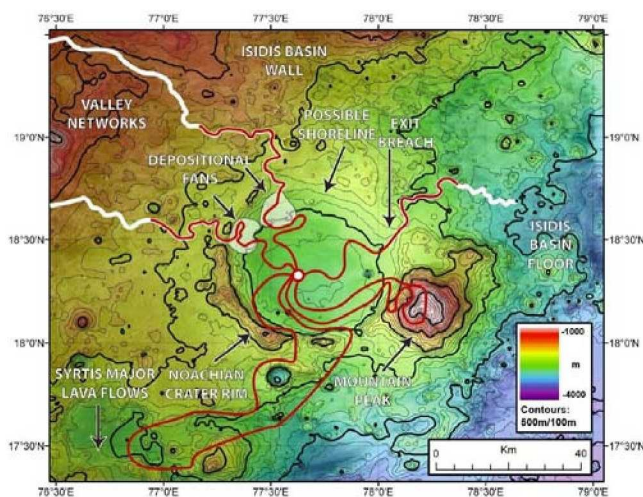


Figure 3 Surface Mobility

The primary habitat would have space and resources allocated for on-board science experiments. The pressurized rovers would carry only the minimal scientific equipment that is deemed essential for field work (in addition to the previously mentioned drill). Samples would be returned to the primary habitat and its on-board laboratory for any extensive analysis.

4. VEHICLE AND SYSTEMS OVERVIEW

Successfully accomplishing the goals and missions set for DRA 5.0 will require a variety of launch, in-space, and planetary surface vehicles as well as specific operational procedures to use them. This section will give an overview of these vehicles and systems, along with a basic description of their operational use.

The technical assessments conducted for the DRA 5.0 focused primarily on launch vehicle, interplanetary transportation, and Entry, Descent and Landing (EDL) systems. Assessments of the applicability of the Orion crew exploration vehicle (CEV) as well as the Mars DAV and the interplanetary transit habitat were also conducted, but not to the same level of detail. Assessments of using the Constellation Program's heavy-lift launch vehicle (HLLV), the Ares V launch vehicle, for a human mission to Mars were examined both in the context of the required performance (e.g., initial mass in low-Earth orbit (IMLEO), number of launches, etc.). For the in-space transportation system for crew and cargo, the design team assessed both nuclear thermal and advanced chemical propulsion, and determined that the NTR was the preferred approach, while retaining chemical/aerocapture as a backup option. In previous design reference missions (DRMs), a small capsule was envisioned for the Earth return vehicle (ERV), but with the design of the Orion CEV there is now a block-upgrade path that would seek to augment the capsule that is currently being designed to go to the moon for use on a round-trip

Mars mission. This would primarily involve upgrading the Thermal Protection System (TPS) on the current Orion design to account for the higher Earth entry speeds and certifying the vehicle for extended dormant times in a space environment.

Additional technical studies associated with surface systems for DRA 5.0 focused primarily on understanding the relationship between the functional capabilities necessary to accomplish the exploration goals and objectives and establishment of the top-level definition of the systems that are necessary for those functions. In most cases, detailed designs for surface systems were not developed but, rather, top-level performance estimates and trades were conducted. More in-depth detailed definition of the various surface systems should be conducted in future efforts, including commonality with lunar surface systems.

Perhaps the most important advancement in knowledge since the last Mars reference mission study involves the EDL systems that are to be employed at Mars to land payloads on the order of 30 to 50 t. Previous estimates of human-class EDL system mass were determined to be optimistic given the great unknowns that are still associated with landing robotic payloads greater than 1 t on Mars. Additional knowledge and insights that were gained with the successful Mars robotic mission EDL designs of the last decade (Mars Pathfinder, the MERs Spirit and Opportunity, and the Mars Phoenix lander) have also resulted in more realistic estimates for EDL system masses required for robust EDL system designs. The new assessment details a more conservative estimate of EDL system mass, which has substantially increased, in spite of the advantage gained from the presumed use of a common Ares V launch shroud/aeroshell payload entry shield. Mass increases in this subsystem are a prime contributor to the overall increase in the initial mass to LEO estimates given in this DRA as compared to previous DRMs.

Interplanetary Trajectory and Mission Analysis

Although no date has been chosen for the first human mission to Mars, high-thrust trajectories were analyzed for round-trip crewed missions to Mars with Earth departure dates ranging from 2030 to 2046. These dates were chosen to assess the variability of mission opportunities across the synodic cycle, and not to represent proposed actual mission dates. Mission opportunities occur approximately every 2.1 years in a cycle that repeats every 15 years (the synodic cycle). (The trajectories from one 15-year cycle to the next do not match exactly, but are very similar and sufficient for initial planning purposes. The duration required for a more exact match is 79 years.) Along with the crewed missions, one-way cargo delivery trajectories were also generated that depart during the opportunity preceding each crewed mission. Each cargo mission delivers two vehicles to Mars.

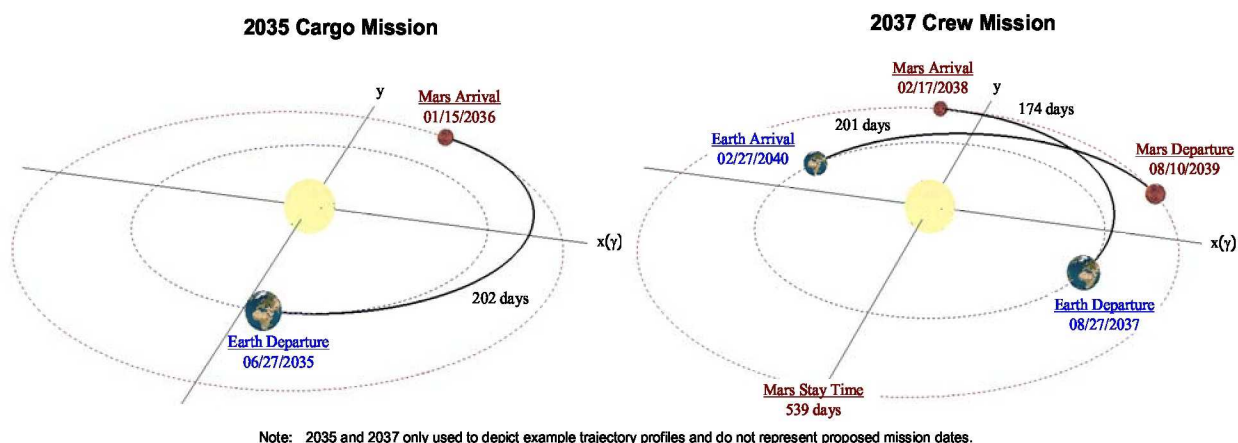


Figure 4 Cargo and crew trajectories for the example 2037 mission

In this analysis, all vehicles depart from a 407-km circular orbit, and a two-burn Earth escape is performed to reduce the gravity loss penalties. At Mars, the vehicles are inserted into a 1-sol elliptical orbit (250 km x 33,793 km). Both propulsive and aerocapture cases were investigated for the cargo missions, while for the crewed vehicles only propulsive orbital insertions were considered.

Representative trajectories for the cargo and crew missions for an example crew mission are shown in figure 4. The displayed crewed profile corresponds to the all-propulsive opportunity with transit times of 174 days outbound and 201 days inbound. The crew's Mars stay time is 539 days, and the total mission duration is 914 days. The supporting cargo vehicle departs Earth a little more than 2 years before the crewed mission two years later and follows a minimum energy trajectory. The trip time of 202 days is the quickest cargo flight time that was observed over the dates analyzed.

Heavy-Lift Launch Vehicle

The reference HLLV that is currently envisioned for NASA's human lunar return is called Ares V by the Constellation Program. Although the Ares V design continues to evolve, the configuration (figure 5) that served as the point of departure for the Mars DRA 5.0 study consisted of two 5-segment reusable solid rocket boosters (RSRBs), a core stage that is powered by five Pratt & Whitney Rocketdyne RS-68B engines, an Earth departure stage (EDS) powered by one Pratt & Whitney Rocketdyne J-2X, and a payload shroud. This vehicle has a gross liftoff mass of approximately 3,323 t (7,326 klbm) and a height of 110.3 m (361.9 ft). Because a new follow-on HLLV that was specifically designed for Mars would be too expensive, emphasis was placed on analyzing how well the various Ares V design options that are currently being designed for the lunar mission could be adapted to meet the mission objectives for Mars. As the Ares V design evolves for the

lunar mission, its capabilities and performance must be continually assessed as to its suitability to meet key Mars mission requirements.

During the Mars architecture study, several different shroud configurations were examined to determine the effect of the shroud dimensions and delivery orbit on overall architecture performance on not only the launch vehicle but the shroud influence on the interplanetary transportation system, the EDL system, as well as other mission payloads. The shroud outer dimensions investigated ranged from 8.4 to 12 m in diameter and 12 to 35 m in length. In addition, the concept of a dual-purpose shroud that would be used for both the launch to LEO and Mars atmospheric entry (i.e., reinforced with TPS for EDL) was examined. The length of this dual-use shroud was defined as 30 m, including the transition cone with an outer diameter of 10 m.

In-Space Transportation: Nuclear Thermal Rocket Reference

During development of DRA 5.0, the design team conducted top-level performance assessments of both the NTR and advanced chemical propulsion. Based on the assessments that were conducted, the team concluded that the NTR was the preferred transportation technology for both the crew and the cargo vehicles and, thus, should be retained as the reference vehicle, with chemical/aerocapture as an option.

The NTR is a leading propulsion system option for human Mars missions because of its high thrust (10's of N) and high specific impulse (Isp 875–950 s) capability, which is twice that of today's liquid oxygen (LO₂)/liquid hydrogen (LH₂) chemical rocket engines. Demonstrated in 20 rocket/reactor ground tests during the Rover/Nuclear Engine for Rocket Vehicle Applications (NERVA) Programs, the NTR uses fission-reactor-generated thermal

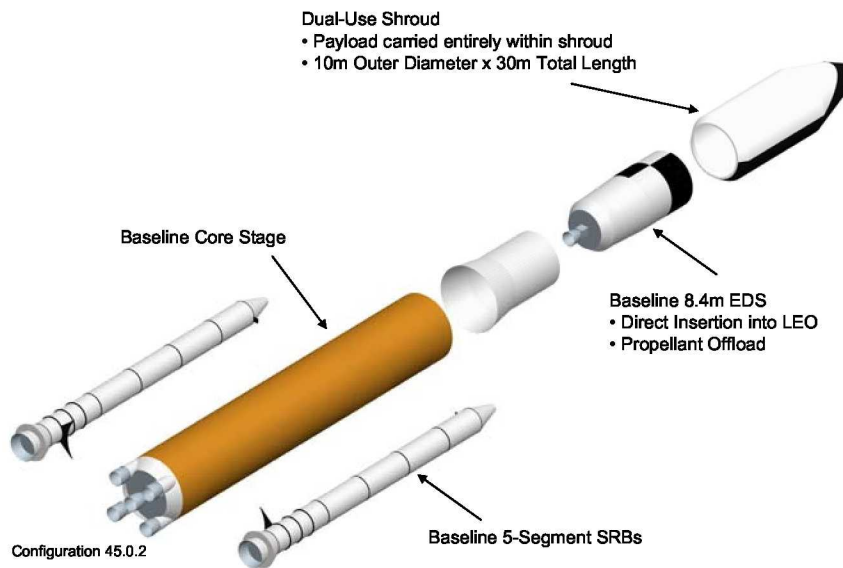


Figure 5 Reference Ares V Heavy Lift Launch Vehicle

power rather than chemical combustion of an oxidizer-fuel mixture to directly heat LH_2 propellant for rocket thrust. NASA's previous Mars DRM studies, DRM 3.0 [7] and DRM 4.0 [8], used a "common" propulsion module with three 66 kN (15 klbf) NTR engines. The use of clustered, lower-thrust engines provides an "engine-out" capability that could increase crew safety and reduce mission risk. The time and cost to develop and ground test these smaller engines is also expected to be less than that required for higher-thrust engines. Both conventional NTR engines (thrust only) and bimodal nuclear thermal rocket (BNTR) engines, which are capable of producing both thrust and modest amounts of electrical power (few 10's of kWe) during the mission coast phase, were examined in addition to zero-gravity and artificial gravity (AG) crewed MTV design concepts. The current Mars DRA 5.0 study efforts considered "thrust-only" NTR engines, zero-gravity crewed MTV designs, and photovoltaic arrays (PVAs) to supply spacecraft electrical power.

The cargo and crewed NTR MTV concepts that were developed for the long surface stay "split mission" DRA 5.0 are shown in figure 6. All vehicles use a common "core" propulsion stage with three 111 kN (25-klbf) NTR engines to perform all of the primary mission maneuvers. In-line and jettisonable drop tanks augment the core stage LH_2 propellant load for the different vehicles as needed. The propulsion stage carries circular Orion-type PVAs for auxiliary electrical power to run key stage subsystems (e.g., zero boil-off (ZBO) LH_2 cryocoolers) as well as a storable propellant Reaction Control System (RCS) for Earth orbit AR&D of MTV components and for orbit maintenance during the LEO loiter phase

Two cargo flights are used to pre-deploy a cargo lander to the surface and a habitat lander into Mars orbit where it remains until the arrival of the crewed MTV during the next mission opportunity. Five Ares-V flights, which are carried out over 120 days, are required for the two cargo vehicles. The first two Ares-V launches deliver the NTR core propulsion stages while the third launch delivers the two short "in-line" LH_2 tanks that are packaged end-to-end. Once in orbit, the in-line tanks separate and dock with the propulsion stages, which function as the active element during the AR&D maneuver. The two aerocaptured payload elements are delivered on the last two Ares-V launches.

Each cargo vehicle has an IMLEO of 246.2 t and an overall length of 72.6 m, which includes the 30-m-long aerocaptured payload. The total payload mass (aeroshell, EDL system, lander descent stage, and surface payload) is 103 t, which is consistent with a surface strategy using nuclear power and in-situ resource utilization (ISRU). The NTR propulsion stage has an overall length of 28.8 m (26.6 m with retracted nozzles for launch) and a launch mass of 96.6 t. The stage LH_2 tank has an inner diameter of 8.9 m and a propellant capacity of 59.4 t. The short in-line tank has a launch mass of 46.6 t and an overall length of 13.3 m including the forward and rear adaptor sections, and it holds 34.1 t of LH_2 . Each NTR cargo vehicle also carries 5.2 t of RCS propellant, which is used for LEO operations, coast attitude control, mid-course correction, and Mars orbit maintenance. Approximately 91 t of LH_2 is used during the TMI maneuver, including the "post-burn" cool-down propellant. The corresponding engine burn time is 39 minutes, which is well within the 62-minute single-burn duration that was demonstrated by the NRX-A6 engine during the NERVA program.

The “all-propulsive” crewed MTV has an IMLEO of 356.4 t and an overall vehicle length of 96.7 m. It is an “in-line” configuration, which, like the cargo MTV, uses AR&D to simplify vehicle assembly. It uses the same common NTR propulsion stage but includes additional external radiation shielding on each engine for crew protection during engine operation. It also includes two saddle trusses that are open on the underside for jettisoning of the drained LH₂ drop tank and unused contingency consumables at the appropriate points in the mission. Four 12.5 kW_e/125 m² rectangular PVAs, which are attached to the front end of the short saddle truss, provide the crewed MTV with 50 kW_e of electrical power for crew life support, propellant tank ZBO cryocoolers and high-data-rate communications with Earth.

Four Ares V launches over 90 days are used to deliver the crew MTV vehicle components, which include: (1) the NTR “core” propulsion stage (106.2 t); (2) an in-line propellant tank (91.4 t); (3) a saddle truss and LH₂ drop tank (96 t); and (4) supporting payload (62.8 t). The payload component includes a short saddle truss that connects the transit habitat and long-lived Orion/service module (SM), which are used for vehicle-to-vehicle transfer and “end of mission” Earth entry, to the rest of the MTV. Also attached to the short saddle truss forward adaptor ring is a T-shaped docking module (DM) that connects the contingency consumables container with the transit habitat’s rear hatch. More importantly, this second DM provides additional access to the MTV for the crew delivery CEV/SM.

For the round-trip crewed mission, the required total usable LH₂ propellant loading is 191.7 t and the corresponding total engine burn duration is 84.5 minutes (57.8 minutes for trans-Mars injection (TMI), 16 minutes for Mars orbit insertion (MOI) and 10.7 minutes for trans-Earth injection (TEI)), which is well within the 2-hour accumulated engine burn time that was demonstrated on the XE engine during the NERVA program.

In-Space Transportation: Chemical/Aerocapture Option

The chemical/aerocapture MTV vehicle concept option for this study was made up of multiple-stage vehicles consisting of separate propulsive elements for each major mission maneuver. The vehicle elements were designed to allow maximum design commonality, efficient Earth-to-orbit delivery, and efficient assembly in LEO. The mission architectures that were considered in this study use two cargo vehicles and one crew vehicle for each Mars mission, as shown in figure 7.

The cargo vehicles would depart Earth approximately 2 years before the crew vehicle. One cargo vehicle would transport the Mars SHAB as payload, and the other would transport the Mars DAV as payload. The cargo vehicles consist of a payload that is enclosed in a cylindrical aeroshell and propulsive stages for TMI. The aeroshell would serve as a payload shroud for Earth-to-orbit launch

and an aerodynamic lifting body for Mars aerocapture, entry, and descent. Depending on the specific trajectory case, two or three TMI modules are required for each cargo vehicle.

The crewed vehicle for interplanetary flight consists of the CEV, transit habitat, three TMI propulsion modules, one MOI propulsion module, and one TEI propulsion module. The CEV is used to transport the crew to LEO prior to TMI. The TMI maneuver is divided into two propulsive burns. The two outboard TMI modules perform the first burn and are then jettisoned. The center TMI module performs the second burn. A separate block upgrade version of the Orion vehicle remains docked to the transit habitat until shortly before Earth return, when the crew would separate from the transit habitat and perform a direct-entry Earth return. Each MTV vehicle in LEO requires a LEO assembly reboost module, which performs attitude control and orbital reboost of the MTV during the LEO periods. The reboost modules are jettisoned from the vehicle stack prior to TMI.

Crew Exploration Vehicle/Earth Return Vehicle

Within the framework of the Mars DRA 5.0, a future block upgrade of the Orion CEV (figure 8) serves two vital functions: (1) the transfer of as many as six crew members between Earth and an MTV in LEO at the beginning of the Mars mission, and (2) the return of the as many as six crew members to Earth via direct entry from the Mars return trajectory. A CEV block upgrade (crew module and SM with a 3-year in-space certification) is launched as part of the crewed payload mass on an Ares V. The ISS version of the Orion, which will be launched by the Ares 1, delivers the six Mars crew members into an orbit that matches the inclination and altitude of the orbiting MTV. It then takes the CEV, which is conducting a standard ISS-type rendezvous and docking approach to the MTV, as many as 2 days to perform orbit-raising maneuvers to close on the MTV. After docking and the crew and cargo transfer activities are complete, the crew delivery CEV is jettisoned in preparation for TMI. The long-lived Orion block upgrade that was delivered on the Ares V is configured to a quiescent state and remains docked to the MTV for the trip to Mars and back to Earth. Periodic systems health checks and monitoring are performed by the ground and flight crew throughout the mission.

As the MTV approaches Earth upon completion of the 30-month round-trip mission, the crew performs a pre-undock health check of all entry-critical systems, transfers to the CEV, closes hatches, performs leak checks, and undocks from the MTV. The MTV is targeted for an Earth fly-by with subsequent disposal in heliocentric space. The CEV departs from the MTV 24 to 48 hours prior to Earth entry and conducts an on-board-targeted, ground-validated burn to target for the proper entry corridor; as entry approaches, the CEV crew module (CM) maneuvers to the proper entry interface attitude for a direct-guided entry to the landing

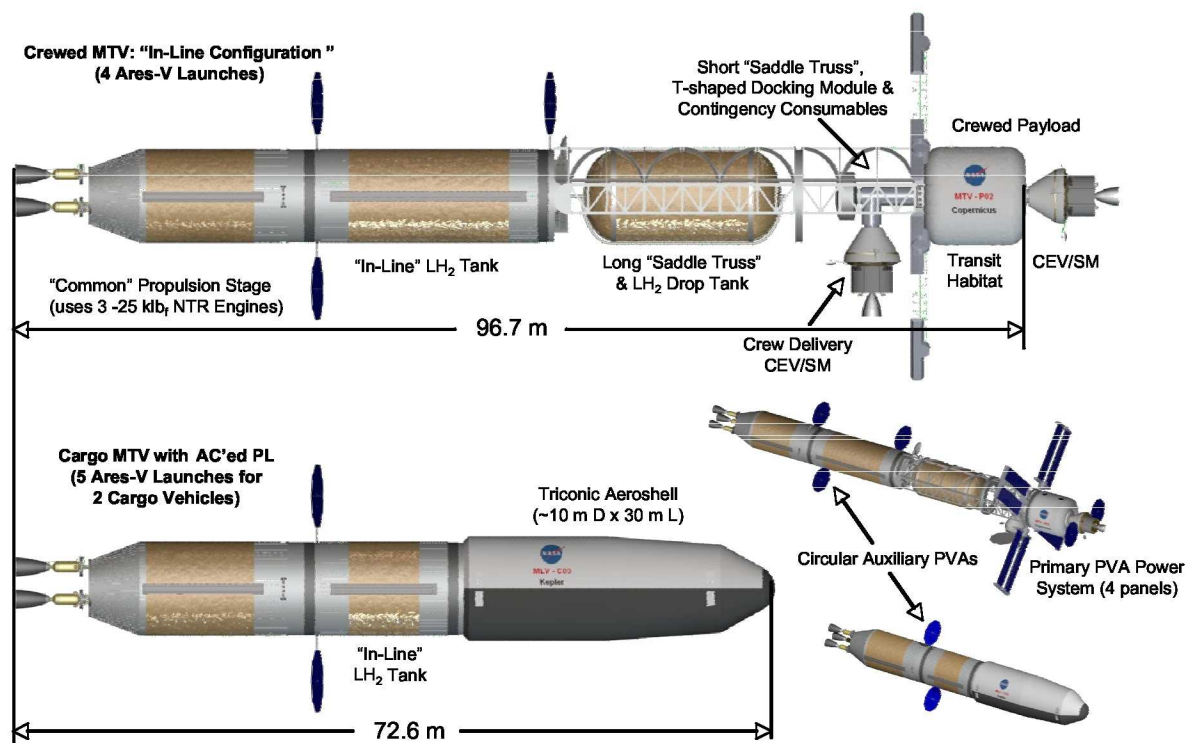


Figure 6 Crewed and cargo NTR design concepts

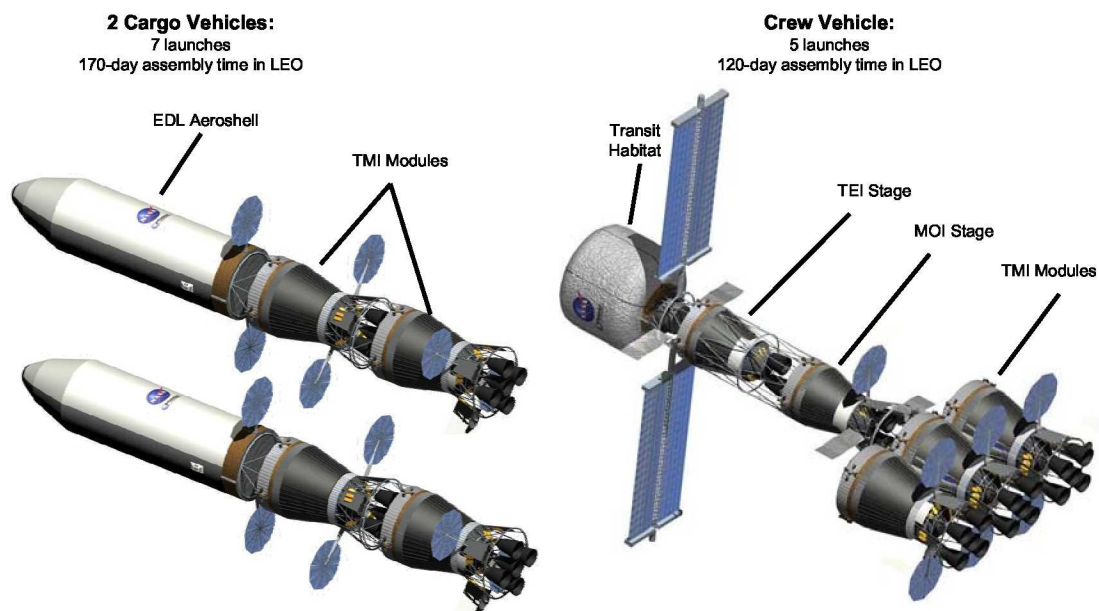


Figure 7 Chemical/aerobrake cargo and crewed MTV concepts



Figure 8 Crew Exploration Vehicle

site. The CEV performs a nominal water landing, and the crew and vehicle are recovered. Earth entry speeds from a nominal Mars return trajectory may be as high as 12 km/s, as compared to 11 km/s for the lunar CEV. This will necessitate the development of a lightweight TPS.

Two other factors (besides the primary concern of Earth entry speed) will drive the evolution of the CEV from a lunar vehicle to a Mars vehicle. The first is the need to re-certify the Orion for a 3-year on-orbit lifetime. Additionally, a science-driven mission to Mars would likely result in the desire to bring back an adequate amount of martian material (the current suggestion is 250 kg). Given the gear ratios involved in a round trip to Mars, the mass of such material would either have to be kept to a minimum or the upgrade

would have to adopt an undetermined strategy by which to accommodate the mass and volume of this scientific material.

It was not within the scope of the DRA 5.0 activity to recommend specific design upgrades for the Orion vehicle or to develop an upgrade strategy. Instead, a mass estimate of 10 t was used for the vehicle CM to size propulsion stages. An additional 4 t was book-kept for a service module that may be needed to perform an Earth-targeting burn. Future activities, likely in conjunction with the Orion Project Office, will better define an upgrade strategy.

Mars Entry, Descent, and Landing Systems

The baseline EDL system design was developed using the 10-m diameter x 30-m length dual-use launch shroud/entry aeroshell and a reference Mars orbit with a 1-sol period (250 km x 33,793 km). EDL system designs were developed for both of the cargo and habitat landers that use aerocapture for MOI while the crewed MTV uses propulsive MOI. In the case where aerocapture was used to

achieve Mars orbit, the same aeroshell was used for both the aerocapture and the EDL phase, although additional TPS mass was required to accommodate the additional heating environment that is associated with the aerocapture maneuver. A pseudo-guidance methodology was developed to provide a realistic entry profile that would minimize terminal descent propulsive fuel requirements as well as the TPS mass and land the vehicle at zero km Mars orbiter laser altimeter (MOLA) reference altitude. Several EDL configuration architectures were considered during this study (details of which can be found in the full report [1]). The reference EDL architecture that was ultimately selected for this study was a hypersonic aeroassist entry system, with a mid lift-to-drag ratio (L/D) aeroshell that was ejected at low supersonic Mach numbers. A LO_2 /liquid methane (LCH_4)-fueled propulsion system was used for de-orbit delta-V maneuvers, RCS control during the entry phase, and final terminal descent to the surface.

The aerocapture and entry aeroshell structure mass estimates were made using preliminary estimates and guidance from the Ares V launch vehicle shroud development efforts. A “dual-use” launch shroud/EDL system approach was used whereby the launch vehicle shroud is used as the EDL structural element. Aerocapture and EDL aeroshell structural mass estimates were based on equivalent area Ares V payload shroud mass sizing plus a 50% margin to allow for the additional lateral loads that are associated with entry and descent, TPS attachment scar mass, heat soak back, etc. The TPS analysis trade studies and sizing were conducted by personnel involved in the Orion – Crew Exploration Vehicle Thermal Protection System Advanced Development Project. The TPS materials selected for the aeroshell forebody heat shield were phenolic impregnated carbon ablator (PICA) and LI 2200. PICA is a candidate Orion/CEV ablator that is being developed for both the LEO and lunar return missions. PICA was the required TPS to account for the relatively high heating rates (462 W/cm²) that were experienced during the aerocapture phase. For the leeward surfaces that are exposed to less severe thermal environments, heritage shuttle TPS materials were selected including LI-900 and felt reusable surface insulation (FRSI) blankets.

The descent stage dry mass is based on mass characteristics that were modeled using the Johnson Space Center (JSC) Envision mass sizing and simulation program. The descent stage is an all-propulsive, legged lander concept that uses four pump-fed LO_2 / LCH_4 engines with the following reference characteristics: an Isp of 369 sec, engine oxidizer-to-fuel (O/F) ratio of 3.5, chamber pressure of 600 pounds per square inch (psi), and a nozzle area ratio of 200. The descent stage engines were assumed, from previous large lander studies, to be RL10 derivatives and further assumed a thrust-to-weight ratio of the engines of 40 lbf/lbm. Recognizing that the LO_2 / LH_2 RL10 may not be the most appropriate analog for the LO_2 / LCH_4 engines that are currently baselined in this architecture, the parametric space

was expanded to include engines that are derived from an RD-180 derivative that has a thrust-to-mass ratio of 80 lbf/lbm. The baseline vehicle was sized to conform to the 10.0-m-diameter aeroshell. The descent stage thrust structure was assumed to undergo maximum loading during the descent maneuver and is sized to withstand the user-defined system thrust-to-weight ratio without the aeroshell attached as payload, assuming that the aeroshell was deployed prior to terminal descent engine initiation. In addition, the tanks of the descent stage are sized to include the deorbit fuel. Additional margin was placed on the terminal descent fuel budget to perform a “divert maneuver” following the heatshield ejection so that the heatshield debris does not impact the surface near any highly valued pre-deployed assets.

Mars Transit Habitat Systems

The crewed MTV consists of propulsion stages and propellant tanks for the TMI, MOI, and TEI maneuvers for both the nuclear or chemical propulsion options; the CEV that serves the function of an ERV for the final leg of the journey home; and a transit habitat in which the crew lives for the round trip between Earth and Mars. It is assumed that the Mars transit habitat will share as many systems as pragmatically possible with the Mars SHAB. The rationale behind maximizing the commonality between these two elements (one that operates in a zero-g environment and the other that operates in a 1/3-g environment) is driven by the desire to lower the development costs as well as to reduce the number of systems that astronauts would have to learn to operate and repair. An even more critical assumption is that the systems comprising the transit habitat (and SHAB) would be largely based on hardware design and reliability experience gained by ISS operations, as well as long-duration surface habitat operations on the lunar surface (i.e., lunar outpost), which would precede any Mars campaign.

The mass estimates for the transit habitat are similar to the estimates that were used in DRM 4.0, but include a few changes in assumptions regarding dry weight margin (doubled to 30%) and the addition of spares for needed maintenance of the habitat.

The food that is carried aboard the transit habitat includes transit consumables that are needed for the round-trip journey plus contingency consumables that are required to maintain the crew should all or part of the surface mission be aborted and the crew forced to return to the orbiting MTV, which would then function as an orbital “safe haven” until the TEI window opens. Any remaining contingency food remaining on board the crewed MTV would be jettisoned prior to the TEI burn to return home.

Surface Systems Overview

Deliberations by the science team supporting this study determined that surface mobility, including exploration at

great distances from the landing site as well as subsurface access, were keys to a robust science program. To understand the implications of these goals on the resulting surface systems, a range of surface strategy alternatives were considered, each of which emphasized a differing mix of mobility, depth of exploration, and duration of exploration in the field. These surface strategies included: (1) Mobile Home: emphasizing long-duration exploration at great distances from the landing site via the use of large, pressurized rovers; (2) Commuter: providing a balance of habitation and small pressurized rovers for mobility and science; and 3) Telecommuter: emphasizing robotic exploration enabled by teleoperation of small robotic systems from a local habitat. Each of these scenarios was used to provide a better understanding of the systems and capabilities that are needed to accomplish surface exploration goals.

The “Commuter” surface mission scenario was adopted as the nominal scenario for this reference architecture. For this study this scenario included a centrally located, monolithic habitat, two small pressurized rovers, two unpressurized rovers (roughly equivalent to the Apollo LRV), and two robotic rovers. Power for these systems would be supplied by a nuclear power plant that would be previously deployed with the decent-ascent vehicle and used to make a portion of the ascent propellant and consumables (H₂O, oxygen (O₂), and buffer gases) to be used by the crew when they arrive. Although traverses would be a significant feature of the exploration strategy that is used in this scenario, these would be constrained by the capabilities of the small pressurized rover. In this scenario, these rovers have been assumed to have a modest capability, notionally a crew of two, 100 km total distance before being re-supplied, and no more than 1 week duration. Thus, on-board habitation capabilities would be minimal in these rovers.

With the limited resources that were available for this study, a very preliminary estimate was made of the mass for each of the surface system elements and their distribution between the two cargo elements that would be used to deliver them to Mars. These preliminary estimates indicate that the maximum payload mass delivered by the cargo element will be approximately 40 t; a detail mass breakdown is provided in the full DRA5 report [1].

Surface Habitation Systems

Development of the Mars DRA 5.0 was conducted at the same time that formulation of various lunar surface scenarios was being conducted by the LAT. One of the key strategies of the lunar missions is the development and demonstration of fundamental exploration capabilities that could be used for future exploration beyond LEO; i.e., Mars. Due to time and resource limitations, a detailed assessment of Mars habitats was not conducted. Instead, emphasis was placed on understanding the fundamental

similarities and differences between the lunar and Mars habitation systems.

Current studies of lunar habitats typically accommodated a crew of four and have varied in general configuration. Modifications were necessary for crew size, overall mission duration, and logistics capabilities of a Mars mission. Due to limited opportunity for logistics resupply for Mars missions, each subsystem determined a spares factor of additional mass to be delivered with the habitat. For totals, a 20% concept design factor was added. The resulting Commuter habitat approach is approximately 21.5 t, using 12.1 kWe of electrical power supplied from an external source. One potential concept as derived from previous lunar studies is shown in figure 9.

A key objective of the Mars surface mission is to get members of the crew into the field where they could interact as directly as possible with the planet that they have come to explore. This would be accomplished via the use of EVAs, assisted by pressurized and unpressurized rovers, to carry out field work in the vicinity of the surface base.

Typical Surface Exploration Campaign

A typical field exploration campaign would begin with a suite of scientific questions in a particular region and the identification of specific surface features, which are based on maps and overhead photos, and that hold the potential for answering these questions. Traverses are planned to visit these sites, typically grouping these sites together (into multiple traverses, if necessary) to meet the limitation of the equipment or environment (e.g., EVA suit duration limits, fueled rover range, crew constraints, local sunset, etc.). Depending on the anticipated difficulty of the planned traverse, the crew may choose to send a teleoperated robot to scout the route that would send back imagery or other data for the crew to consider. In addition, crew safety concerns when entering a region that is highly dissimilar from any explored before or an area with a high potential for biological activity may dictate the use of a rover in advance of the crew.

Several key scientific and operational questions would require subsurface samples that are acquired by drilling. Examples include searching for subsurface H₂O or ice, obtaining a stratigraphic record of sediments or layered rocks, or obtaining samples to be used to conduct a search for evidence of past or extant (possibly endolithic) life. Drill equipment would be moved to the site, most likely on a trailer that is pulled by either the unpressurized or robotic rovers, and set up for operations. The set-up process would likely be automated, but with the potential for intervention by the crew. Drilling operations are also likely to be automated but under close supervision by the crew. At present, drilling is still something of an art, requiring an understanding of both the nature of the material being drilled – or at least a best guess of the nature of that material



Figure 9 Mars habitat concept based on lunar architecture options

– and the equipment being used. While drilling is a candidate for a high level of automation, it is likely that human supervision for purposes of “fine tuning” the operations and intervening to stop drilling would remain a hallmark of this activity. Core samples would be retrieved by the crew and put through an appropriate curation process before eventual analysis. After concluding drilling at a particular site, the drill equipment would be disassembled and moved to the next site, where this procedure would be repeated.

As is apparent in the previous discussion, conducting scientific investigations on the surface of Mars would require extensive EVA to take advantage of the human element over robotic rovers. The EVA system, therefore, is a critical element in maximizing the science return from a human Mars mission. The EVA system that is currently under development for the lunar surface would require modifications to operate under environmental conditions on Mars. Three characteristics of the Martian environment dictate this: (1) increased value of the surface gravity from 1/6 g on the lunar surface to 1/3 g on Mars; (2) the change in the atmosphere from essentially vacuum to an approximately 10 mbar CO₂ and argon (Ar) atmosphere; and (3) the requirement to minimize contamination of the Martian environment and exposure of astronauts to Martian materials.

Surface Transportation: Unpressurized and Pressurized Rovers

Even at distances that are considered within walking range, incorporation of surface transportation has been found to enhance crew productivity, both to mitigate crew fatigue and to extend consumable supplies by allowing lower metabolic rates during seated travel. Providing the capability to travel easily and quickly away from the landing site would be necessary for the crew to remain fully productive throughout the surface mission.

The unpressurized rover could be viewed in many ways as an extension of the EVA suit. From this perspective, many of the heavier or bulky systems that would otherwise be an integral part of the suit could be removed and placed on the rover, or the functionality of certain systems could be split between suit and rover. In the case of offloading capabilities to the rover, navigation, long-range communication, tools, and experiment packages could be integrated with or carried by the rover. In the case of splitting functionality, any of the various life support system consumables (e.g., power, breathing gases, thermal control, etc.) could be located on both the rover and within the EVA suit. This division or reallocation of EVA support functionality may restrict the maximum duration of the EVA suit to something less than that which has been previously demonstrated. However, analysis of Apollo LRV exploration indicates that approximately 20% of the total EVA time was spent by the crew on the LRV moving from site to site. Mars surface operations could be assumed to be comparable. Thus the EVA team would have sufficient time for recharge of EVA suit consumables or switching to rover-based support systems to preserve EVA suit consumables. Providing multiple sources of consumables and support systems in the field also enhance crew safety by providing contingency options should EVA suit systems degrade or fail.

Operationally, Mars surface EVAs would be conducted by a minimum of two people and a maximum of four. (This would always provide for a “buddy system” while on an EVA but would also leave at least two people in the SHAB for contingency operations should they be needed.) If unpressurized rovers are used, an additional operational constraint would be imposed on the EVA team. If one rover is used, the EVA team would be constrained to operate within rescue range of the surface base. This could mean either the team has sufficient time to walk back to the surface base if the rover fails, or that there is sufficient time for a rescue team from the surface base to reach them. Taking multiple, and identical, rovers into the field allows the EVA team to expand its range of operation because these vehicles are now mutually supporting and, thus, able to handle a wider range of contingency situations. Operationally, the rovers must be reliable but also easily repairable in the field (or at least have the capability of being partially disassembled in the field so that the failed component could be returned to the outpost for repair). The

rovers must also be sized to carry cargo that, if offloaded, is of a sufficient capacity to carry the crew of a disabled rover.

Pressurized rovers are typically included in the Mars mission studies because of their ability to extend the range of the crew, in terms of both distance and duration. While exact distances and durations would be dependent on the specific site chosen, input received from the science team supporting this study indicates a strong desire to reach locations several hundred kilometers from the outpost for durations measured in days to weeks between resupply. It was also the intent that the crew using the pressurized rover be capable of performing many of the same functions as at the outpost, albeit at a reduced scale. Thus a crew using a pressurized rover could be expected to be capable of commanding and controlling teleoperated rovers, conducting EVA activities (comparable to those discussed earlier) within the vicinity of the rover, and otherwise supporting the crew for the duration of its excursion away from the outpost.

For this DRA assessment, a modest pressurized rover capability was assumed. This rover was scaled to support a crew of two (with the ability to support four people in a contingency) for a period of approximately 2 weeks without resupply and travel for a total distance of approximately 100 km. These two pressurized rovers are assumed to be nimble enough to place the crew in close proximity to features of interest (i.e., close enough to view from inside the rover or within easy EVA walking distance of the rover).

In-Situ Resource Utilization System

The ISRU plant is designed to convert Mars atmosphere into O₂ for use as propellants and life support. In addition to O₂, the ISRU system generates H₂O and buffer gases for use in the surface habitats and mobility systems. The plant is made up of solid oxide CO₂ electrolyzers (SOCEs) that convert CO₂ into O₂ and carbon monoxide (CO), which is vented. The CO₂ is obtained via a micro-channel adsorption pump. The CH₄ fuel that is required for ascent is brought from Earth. Hydrogen (H₂) (400 kg) is brought from Earth and reacted with Mars-produced O₂ to make up H₂O that is lost during crew and EVA operations. Besides CO₂, N₂ and Ar are also separated and collected from the Mars atmosphere for use as a buffer gas for crew breathing. Because the plant is driven more by power than mass, redundancy is accomplished by the use of two separate ISRU plants, each sized to generate the needed consumables. The mass, power, and volume of the system and associated components is documented in the full DRA 5.0 report [1]. These estimates are based on continuous propellant production, which is provided by a nuclear fission power source. Power estimates for a solar-based system are much higher since propellant production could only be done during the day, which requires a far greater processing rate and subsequent power level.

Stationary Surface Power System

The reference stationary surface power generation system is a nuclear fission power reactor concept that is based on a lunar design. This lunar system was conceived to be easily adaptable to operation on the Martian surface. The low operating temperature of the reactor fuel enables use of stainless steel for major reactor components, a material that is compatible with Mars' predominately CO₂ atmosphere. The nuclear power system's mass used for comparison was for a 30-kWe version of the 40-kWe lunar design to match the requirements of the Mars mission. The reactor would be landed in the DAV in a stowed configuration and offloaded from the cargo bay for emplacement using a utility power cart that would have multiple functions.

The primary surface reactor has an external shield to protect the crew from radiation. Similar to the lunar application, this study has adopted a guideline of less than 5 rem/yr dose to the crew from reactor-generated radiation. Since the shield is a significant portion of the system mass, a shaped shield is employed whereby the radiation at 1 km distance is limited to 5 rem/yr in the direction of the habitat and 50 rem/yr in all other directions. This creates a small exclusion zone but still allows limited passage through the zone under special circumstances. The reactor would be driven about 1 km from the lander that is feeding out the power cable. Once at the site, the mobile chassis would be aligned to properly orient the shield, leveled, and secured by jacks. The DIPS cart, which would be outfitted with appropriate equipment, would assist in the deployment of the radiators if needed. The power cart would be driven back to the landing site and the reactor would be started. It was assumed that the total time to perform this is 30 to 40 sols.

The power that is required for the various architecture elements for normal day and night operations is documented in the full DRA 5.0 report [1]. The habitat power estimate is a modified lunar concept that has been scaled for Mars operations. Power systems were sized for a 12-kWe day/night load for the habitat when using the ISRU-produced O₂ supply. Additional habitat power would be required for closed-loop air revitalization. The ISRU plant, which is making ascent stage O₂ propellant, is the dominant power requirement at 25 kWe operating continuously. After propellant production has been completed, most of the power demands are in support of nominal outpost operation, including habitats, logistics systems, rovers, scientific systems, and ascent stage keep-alive power. Thus, a power system that is sized to meet the ISRU consumable production requirements would have ample power available for crew outpost operations.

Mobile Surface Power System

In addition to the main base power system, options were looked at for powering the surface mobility systems (rovers). The reference "Commuter" strategy has two small

pressurized rovers that would support a crew of two and traverse 100 km in 15 days. A nominal drive time was assumed to be 5 hours each day, which dictated a speed of 3 km/hr to cover the total distance in the time allocated (driving was only during sunlight). In addition, a "trafficability" factor of 30% (avoid rocks, steep grades, soft sand, etc.) was assumed to capture an "odometer" distance that rover speed would be based on, thus a total of 130 km is actually traversed during the sortie. A trade study conducted for this effort determined that a Dynamic Isotope Power System (DIPS), using Plutonium 238 as the energy source, would be used for the power cart and could also be an option for powering the pressurized rovers. The Plutonium 238 isotope, which has fueled numerous deep space missions as well the two Viking landers and long-term experiment packages on Apollo, would be used with advanced power conversion technology to increase power output from three- to four-fold when compared with thermoelectric devices that have been previously used. The advantage of this technology is that continuous power is available from this unit without need for any recharging.

5. KEY CHALLENGES

Missions to Mars represent the next plateau in human exploration of space. Just as Mercury, Gemini, and Apollo grew out of the technology and experience base of the aircraft and missile industry, Mars missions will be an outgrowth of our technology and experience base of Apollo, Shuttle, and ISS in combination with other technologies are recognized as necessary to reach this plateau. There are significant challenges that must be overcome to successfully complete a Mars mission (Table 1), but NASA has historically used the creative talents of its workforce to find the ways and means to successfully carry out its assigned missions that more than satisfies the stakeholders; this same workforce will apply this same creativity to the new objectives of returning to the Moon and sending people, for the first time, to Mars.

Before the first human crew ever departs on a Mars mission, new technologies and capabilities will be developed that will enhance crew health and safety, provide capabilities for these crews to live and work that were not previously available, improve the performance of vehicles already being used, and give access to mission information of unprecedented breadth and quality. It is already known that for a Mars mission to succeed investments must be made to address a broad range of issues: medical research so the crews can live and work productively for several years away from Earth; energy research so the crews can be more productive with the limited energy resources they bring along or gather once they arrive; efficiency and recycling innovations so the crews can minimize the supplies they must bring with them and the impacts they make on the Martian environment; information research so that the information and knowledge resulting from these missions is

captured and shared over a broader range of our population as quickly as possible. All of these capabilities are basic to the success of Mars missions. But as James Michener once said *“The high technical requirements for success in space are so fundamental that spin-off rewards are almost automatic... No one today can even guess the limits of either the personal items or the industrial which might accrue from the basic scientific work that has to be done in a space program.”* These technologies and capabilities, both planned and unanticipated, will be developed here on Earth and will be available not only for Mars missions but for use in a broad range of terrestrial applications.

Human Health and Performance

As humans extend their reach beyond LEO to the surface of Mars, they will be exposed to the hazardous environment of deep space for lengthy periods; consequently, protective measures must be devised to ensure crew health and maximize mission success. The health and safety of crew members while they travel to and from the Mars and inhabit its surface are key near-term concerns. The explorers must be protected from the space radiation environment and from the physiological effects of reduced gravity. To maintain the fitness and productivity of the crew, medical care must be provided during long stays in very isolated and distant places. A thorough ground-based research program that is coupled with flight research on the ISS and missions beyond low-Earth orbit must be conducted to provide an understanding of the physiological basis for human responses, develop appropriate treatments and countermeasures, and decide how best to support crew members.

- Radiation protection from both galactic cosmic radiation as well as solar proton events. The solution may be a combination of uncertainty reduction, shielding, mission design, and crew selection with effective biological countermeasures
- Countermeasures to ameliorate bone mineral loss and muscle atrophy in reduced-gravity environments for both the transits to and from Mars, as well as the long-duration stay on the surface
- Medical care to ensure crew health and performance with limited mass, volume, power, and crew training
- Improved behavioral understanding in order to measure, monitor, and predict mood and psychiatric conditions prior to and during long-duration remote space missions

Without advances in the human support area mission durations may be limited to less than what is required for a round-trip mission to Mars. Advances in these areas of research and technology will contribute to improved health care here on Earth, from a better understanding of human physiology and the causes of certain diseases to improved

means to diagnose and treat individuals in a more comprehensive and efficient manner.

Landing Large Payloads on Mars

Our current ability to land robotic payloads on the surface of Mars is largely reliant on the Entry, Descent, and Landing (EDL) technology set that was developed during the Mars Viking Program in the late 1960s and early 1970s. NASA’s flagship 2011 Mars mission, the MSL, has reached the landed payload mass limit capability (approximately 1 t). The very low atmospheric density at Mars prevents the use of traditional terrestrial aerodynamic decelerators as a means by which to attain subsonic velocities for landing as is done on Earth. Development of a human-rated high mass (40 t useful payload) Mars entry system remains a challenge. NASA has identified several approaches that will overcome this challenge that involves a combination of basic research in hypersonic aerodynamics, materials science, and propulsion technology to deliver these larger payloads.

Heavy Lift

Even with the incorporation of numerous advanced technologies, human missions to Mars require total mission mass on the order of 800-1,200 t for each mission. (Note that at assembly complete the International Space Station will have a combined mass on the order of 400 t.) The ability to launch large payloads, both in terms of mass and volumes, will be required in order to minimize the number of launches as well as complexity of assembly operations. The Ares V heavy-lift launch vehicle required for human Mars missions would have broad applications to a range of both human and robotic missions beyond low-Earth orbit as well as other agencies. This launch vehicle would be the only one in the world and clearly give the US a significant advantage. This also represents a reasonable progression in the development of this transportation capability. Just as the demands for more efficient transportation drove the airline industry from the venerable Douglas DC-3 to the Boeing 747, reaching this next plateau in the exploration and utilization of space leads to the development of a transportation system that can deliver these large payloads in a reasonable (i.e., efficient) number of launches.

Using Local Resources

The use of resources found at Mars (In-Situ Resource Utilization, ISRU) would provide substantial benefits by dramatically reducing the amount of material that must be transported from Earth to a planetary surface. ISRU is a critical component of long-term, largely self-sufficient operations. By extracting and processing local resources to obtain or make O₂, H₂O, CH₄, and buffer gas consumables for life support, EVAs, and ascent propulsion, significant mass reductions or increased payload to the Mars surface is possible. This is also the first step in bringing this and other

Table 1 Comparison of Lunar and Mars Mission Challenges

	Moon	Mars
Distance from Earth	384,000 km	58,000,000 – 400,000,000 km
Two-Way Communication Time	2.6 seconds	6.3 – 44.5 minutes
One-way Trip Time	4 days	180-210 days
Stay Time	7 days (sortie mission)	495 – 540 days
Total Mission Duration	18 days (sortie mission)	895 – 950 days
Aborts	Anytime return	Limited to early in the mission or multi-year
Logistics Delivery	Daily	Every 26 months
Total Mission Mass (Note: ISS ~ 400 t)	~200 t	~800 – 1,200 t
Total Delta-V (LEO to surface and back)	9.5 km/s	12 – 14 km/s

solar system bodies into the Earth's economic sphere, opening the possibility of both bringing resources back to Earth and freeing people to focus on living and working on another planet instead of worrying about getting there (and getting back).

Advanced Propulsion

Although human expeditions to Mars could be conducted using cryogenic propulsion and aerocapture, nuclear propulsion presents a compelling prospect for tremendously reducing the mass or travel time required. Advanced propulsion concepts including space storable landers (oxygen/methane), nuclear thermal propulsion, and the ability to store and manage cryogenic fluids for long durations are required. Development and demonstration of advanced, long-duration transportation concepts to understand their performance and reliability is a key element in future human exploration missions.

Robust Power

Providing robust continuous surface power is critical for future exploration of the martian surface. Due to the distance from the sun as well as environmental conditions on the surface of Mars (atmosphere, dust, winds, etc.) football field size arrays would be required for a solar power approach sufficient to provide the power requirements of a nominal Mars mission. On the other hand, fission surface power (FSP) approaches are a very promising approach to providing a compact and robust continuous power source for future human exploration. The technological approach for this power system is well within the experience base of this industry but will require a typical system development effort for these missions. An added benefit to this approach is that a single system development

could be used, with minor modifications for the local environment, on the Moon, on Mars and in deep space. Solar array approaches, while also within the current technology base, would require unique system developments for each location. Radioisotope power generation systems also have shown to promise as mobile power systems as well as back-up power sources for the crew habitat in emergency systems.

Reliability and Supportability

Resupply capability (from Earth) for human Mars missions are essentially nonexistent. All resources that are required to support the mission must be pre-positioned or carried with the crew, with the exception of resources that are generated in-situ. These missions would also face mass and volume limits that would restrict sparing options and strategies. These two constraints highlight the need for, and challenge of, high reliability and a self-sufficient supportability approach. It would be necessary for the crews of these missions to have at hand all of the resources that are necessary to sustain critical spacecraft systems and support equipment for the duration of their time away from Earth. This capability must be provided while minimizing associated mass and volume requirements.

This self-reliance would be achieved, in part, by increasing emphasis on maintenance by repair rather than replacement. A repair-centered maintenance approach would only be effective, however, when it is strategically coupled with hardware design that is specifically structured as part of the supportability concept.

6. SUMMARY

This paper provides a vision of a potential approach for human Mars exploration that is based on best estimates of what we know today. The strategy and implementation concepts that are described here should not be viewed as constituting a formal plan for the human exploration of Mars. This is the latest in a series of Mars reference missions that are used by NASA to provide a common framework for future planning of systems concepts, technology development, and operational testing. This architecture description provides a reference for integration between multiple agency efforts including Mars robotic missions, research that is conducted on the International Space Station, as well as future lunar exploration missions and systems.

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BIOGRAPHIES

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David W. Beaty: David Beaty is currently the chief scientist for the Mars exploration program at the Jet Propulsion Laboratory in Pasadena. His PhD research at Caltech involved work on samples returned by Apollos 11 and 12. After leaving Caltech in 1980, Dr. Beaty entered the minerals industry with Noranda Exploration. He worked on commercial mineral exploration projects throughout the Rocky Mountains, primarily on projects related to zinc, molybdenum, gold, silver, and copper. In 1988, Dr. Beaty switched to the oil industry, joining Chevron at their research lab in La Habra, CA. After a time as a research geologist, he became interested in management, and moved from team leader to division manager to acting lab director. In 1999 Dr. Beaty left the industrial sector, and returned to the NASA working on planetary robotic missions at JPL. His JPL assignments have included Project Manager, Mars Planetary Protection Manager, Mars Subsurface Exploration Manager, Mars Program Science Manager, and Mars Chief Scientist.